2009 November 30

To: Mu2e Collaboration
From: M. Syphers
Subject: On the Mu2e Operating Scenario

Over the past several months, a number of operating scenarios for the Mu2e experiment have been explored. Here we present arguments that hopefully will lead to a choice for delivering beam to Mu2e. An emerging preference is to provide for a fast kicker system at the extraction point (to the P1 line) of the Recycler which would enable beam to be injected and immediately extracted while circulating beam destined for the neutrino program is present in the storage ring.

1 Background

The Mu2e experiment needs bursts of protons delivered on target with 30-40 ns rms pulse width (presumed Gaussian) every $\sim 1.7\ \mu$s (which corresponds with the revolution time of the Debuncher ring). The total number of protons to be delivered on target for the experiment is $\sim 4 \times 10^{20}$ each year for two years.

In the Proposal, three Booster batches of 4×10^{12} (4 Tp) are delivered twice each NOνA cycle of 1.333 s. The average rate is thus 18 Tp/s. The instantaneous rate on target, assuming two 600 ms spills every NOνA cycle, would be 34 Mp/burst.

In the Proposal's scenario, a number of potential issues have been identified. Namely,

1. Three Booster batches would be accumulated in the Accumulator ring and a single bunch of 12 Tp would be formed and transfered to the Debuncher, where it is phase rotated into a 30 ns (rms) bunch. The space charge tune shift in this scenario is approximately 0.1, believed to be large for a slow spill operation, not to mention for RF beam loading and stability issues, particle loss rates, *etc.*

2. The scenario is dependent upon the cycle time of NOνA. Should this cycle time be different (1.5 s rather than 1.333 s, for example), the experiment would not be able to take advantage of the spare Booster cycles. In fact, if the neutrino experiment were down for some period (such as for a horn change) the Mu2e experiment would not be able to take beam at a much (if any) higher average rate, even though over 3 times more Booster cycles would become available for use.

3. Several new high-voltage RF systems are required for the beam processing. The Accumulator requires a 53 MHz, a 2.5 MHz, and a 0.6 MHz system, and the Debuncher requires 0.5 MHz and 2.4 MHz systems. While some systems do exist at these frequencies in

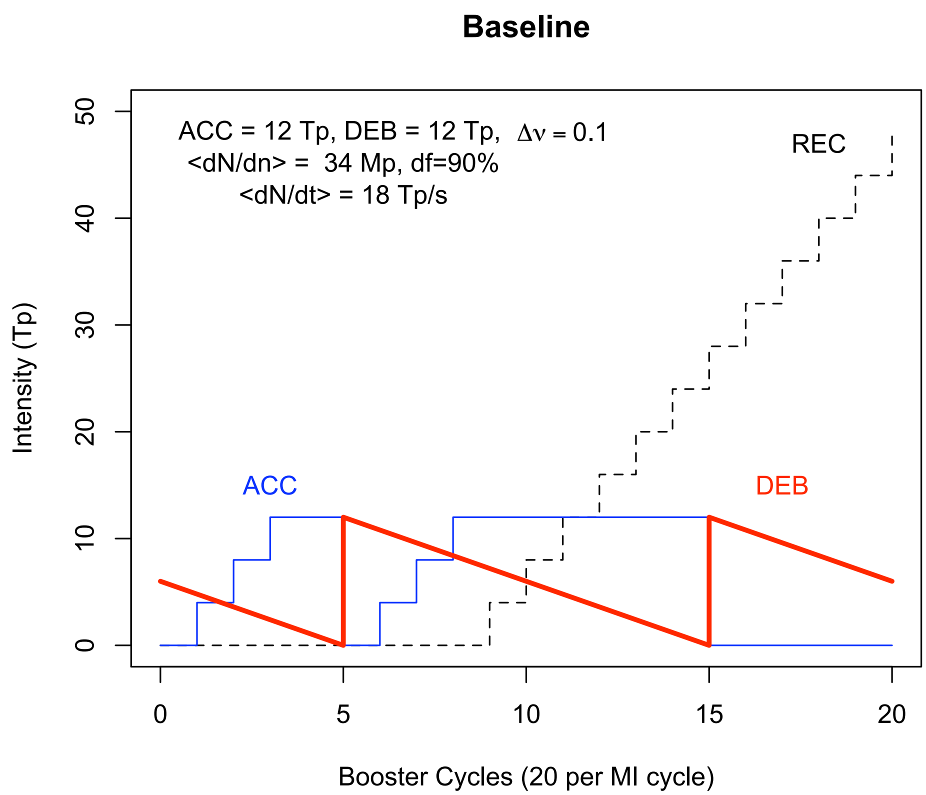

Figure 1: Beam intensities in the Recycler, Accumulator, and Debuncher rings under the Baseline scenario from the Mu2e Proposal. A 90% duty factor is assumed per spill.

these storage rings, the demands on beam intensity and phase space density, phase rotation times, and final bunch length will require much higher voltages than at present, and thus extensive upgrades to all systems will be required.

4. The Booster synchrotron is assumed to be running at a flat-out rate of 15 Hz during Mu2e operation. Today, the Booster runs with beam at an average rate of approximately 3-4 Hz, and can achieve approximately 9 Hz, foreseen for NOνA operation. Upgrades are envisioned which would allow for full 15 Hz operation. Should the Booster not be able to achieve full 15 Hz operation, this could jeopardize the Mu2e run scenario, depending upon the details of the achievable level of repetition.

5. If the Booster does indeed run at 15 Hz, the present Mu2e scenario only uses 6 of the available 8 Booster cycles remaining after the NOνA pulses, as the Accumulator can only accumulate up to three Booster batches within its available aperture. Thus, one-fourth of the Booster cycles available to Mu2e would be unusable by the experiment.

Figure 1 shows beam intensities in the various rings under the Baseline scheme. The experiment has requested average proton rates to the production target similar to the baseline (18 Tp/s), with as high a duty factor as practical, 90% in the Baseline scheme. To set the scale, if the experiment were not tied to NOνA but rather had all Booster cycles at its disposal, one could imagine forming a bunch or bunches from a Booster batch and extracting all within a single Booster cycle — 4 Tp extracted within about 66 ms. This would give an average rate on target of 60 Tp/s, three times the baseline number, and, multiplying by 1.7 μs per burst, gives an instantaneous rate to the target of 110 Mp/burst (assuming a 90% duty factor). These could be considered the approximate upper limits for proton rates on target that could be provided to the experiment by the present Booster. The average power on target under these conditions would be approximately 90 kW, compared to the baseline figure of 26 kW.

2 The g-2 Option

An early alternative that was considered for Mu2e was to use the bunch formation scheme envisioned for the New g-2 Experiment and documented in their proposal.[1] As g-2 is to form 4 bunches in the Recycler spaced in 2.5 MHz buckets, these could be formed for Mu2e as well, and transfered to the Accumulator where they would be injected one-at-a-time into the Debuncher for short-duration slow spills. This reduces the space charge by at least a factor of 12 and simplifies some of the RF procedures in the pbar rings, though new kicker requirements would be in order. As the operation is performed over a Booster cycle, Mu2e would receive beam over 6-8 15-Hz cycles out of 20, and thus would have an overall ~30% duty factor. Figure 2 indicates the scenario for 6 or 8 available Booster pulses per MI cycle, assuming a total average throughput of 18 Tp/s to Mu2e. Of course, if all 8 excess cycles could be used for Mu2e then the overall intensities (and space charge) used in the operation could be lowered and still produce the same average rate of protons on target.

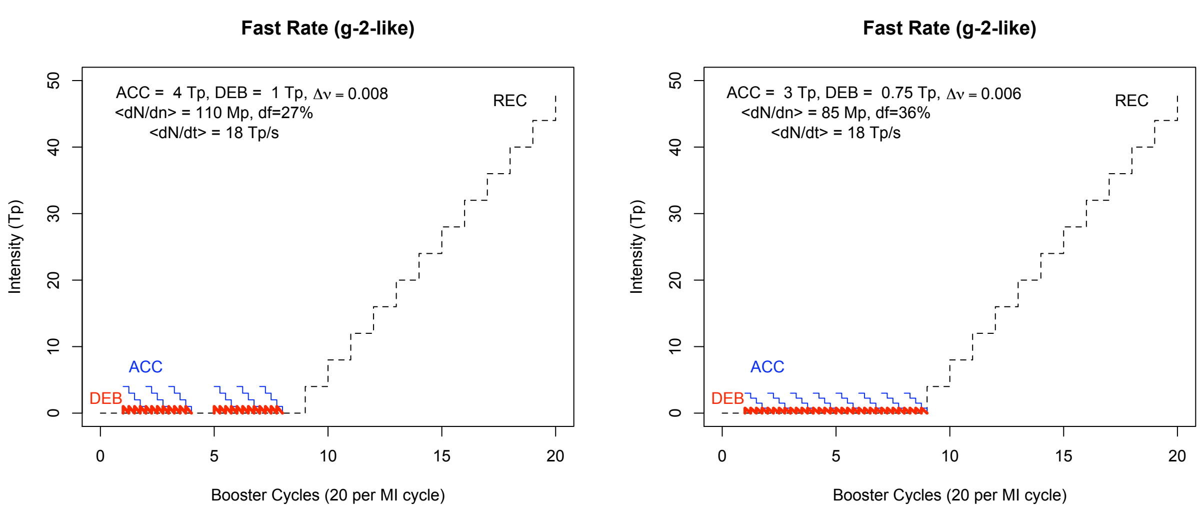

Figure 2: Beam intensities for a "g-2-like" scenario, where 6 (left) or 8 (right) available Booster cycles are used for Mu2e for an average delivery of 18 Tp/s, with 90% duty factor per spill.

[1]See Mu2e-doc-398.

While the ∼100 kW, 100 Mp/burst rates are consistent with the MECO proposal, many on the experiment believe these numbers to be too high for Mu2e, dictated by acceptable background levels at these rates of protons on target while presuming the baseline muon production rates. Hence alternate solutions have been sought.

3 Alternate Mu2e Scenario for Consideration

If one limits the rate to the proposal's 34 Mp/burst, then the only path for improvement is to break the accumulated 12 Tp beam into a number of smaller pieces and spill over a larger number of shorter time intervals. For example, one can accumulate as in the baseline, and form 4 bunches of 3 Tp, transfer one-at-a-time into the Debuncher, and spill over ∼150 ms, rather than the 600 ms. However, as can be seen from Figure 1, this cannot be accomplished while limited to only the first 8 pulses of the Booster under the Baseline scheme. It *can* be accomplished if one is willing to allow Mu2e beam to be "threaded" through the Recycler while beam destined for NOνA is present.

With beam coasting in the Recycler, there is room to inject and immediately extract a Booster batch that would be sent toward Mu2e. Because of the slip-stacking operation, fast rise- and fall-time kickers are being developed for Recycler injection to be used during NOνA operation. A second set of similar kickers could, in principle, be installed at the extraction point to send beam toward the P1 beam line and on to the Accumulator. Booster beam can be transfered for Mu2e interlaced with the first six injections heading for NOνA. The final six requiring slip-stacking would be injected consecutively just before transfer to the Main Injector. In this way, beam can be sent to the Accumulator mid-way through an MI cycle, as shown in Figure 3, which allows for the Accumulator beam to be formed into 4 bunches and transferred to the Debuncher one-by-one for 150 ms slow spills. This "hybrid" scheme would remove the need for high voltage h=1 RF in the Accumulator (though a low-voltage system may still be desired for smoother bunch rotation and capture), and the bunch intensity would be reduced by a factor of 4. In the figure shown, ∼33 ms is left available in the Accumulator before the spills begin for stacking and bunch formation/manipulations. Bunches of the desired length and intensity can be formed within this time frame.[2]

Should the total charge in the Accumulator or Debuncher be of further concern, the hybrid scheme also generates an amount of flexibility in the timeline of Mu2e pulses from the Booster. With this same basic kicker and RF arrangement, pulses to the Accumulator could be more spread out during the MI cycle. For example, if only two Booster batches were accumulated at a time rather than three, then three such occurrences could take place during the MI cycle and slow spilled over about 90 ms each spill, as indicated in Figure 4. For the same average rate of 18 Tp/s, the Accumulator total charge is reduced by 33%, and space charge effects by a factor of at least six (from the Baseline) during extraction from the Debuncher. The duty factor is reduced from about 90% to about 80%, with a 10% higher instantaneous rate to the experiment. In this depiction, about 33 ms is allowed for the momentum stacking and bunch formation once the second Booster batch arrives in the Accumulator.

[2]See D. Neuffer, Fermilab-CONF-09-513-APC (2009).

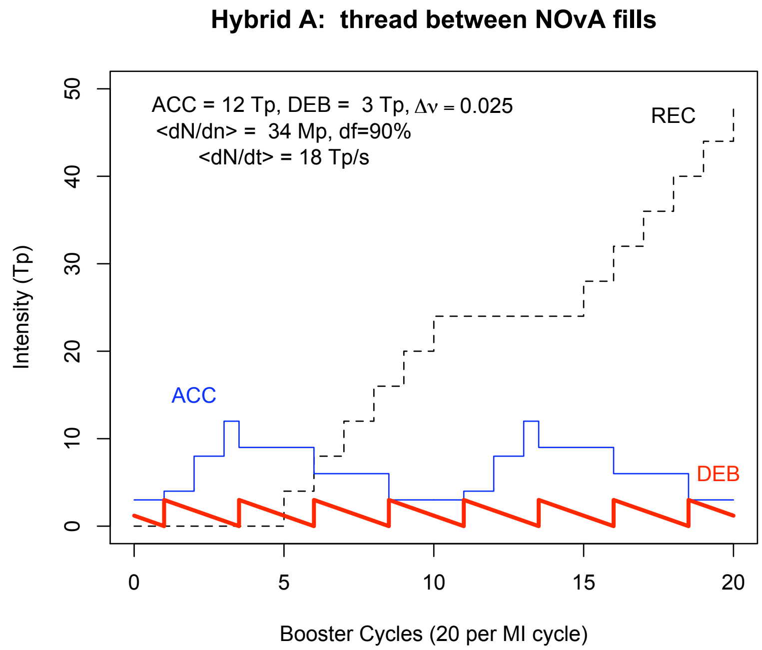

Figure 3: A "hybrid" scheme, where beam is "threaded" through the Recycler mid-way during the NOνA filling process. A 90% duty factor is assumed per spill.

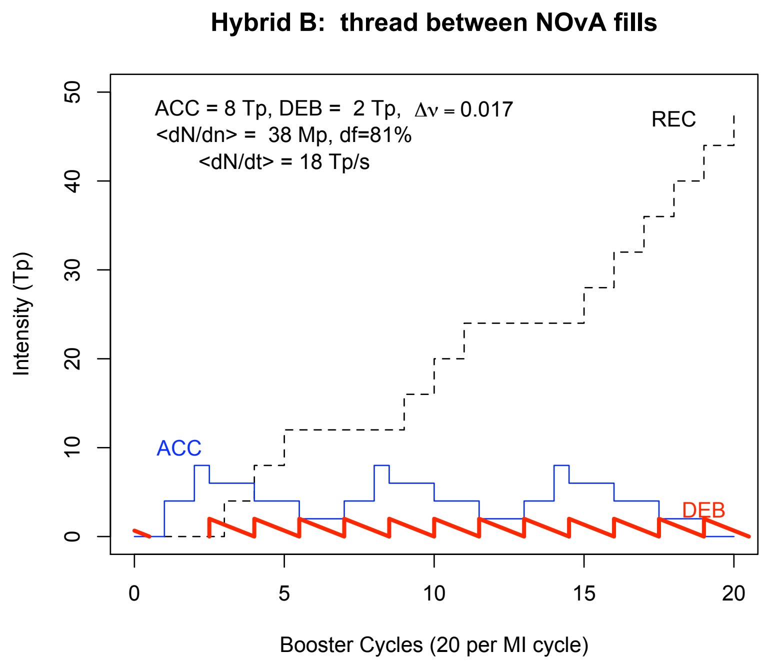

Figure 4: A variant of the above hybrid scheme, with lower Accumulator and Debuncher intensities using shorter spill times. A 90% duty factor is assumed per spill.

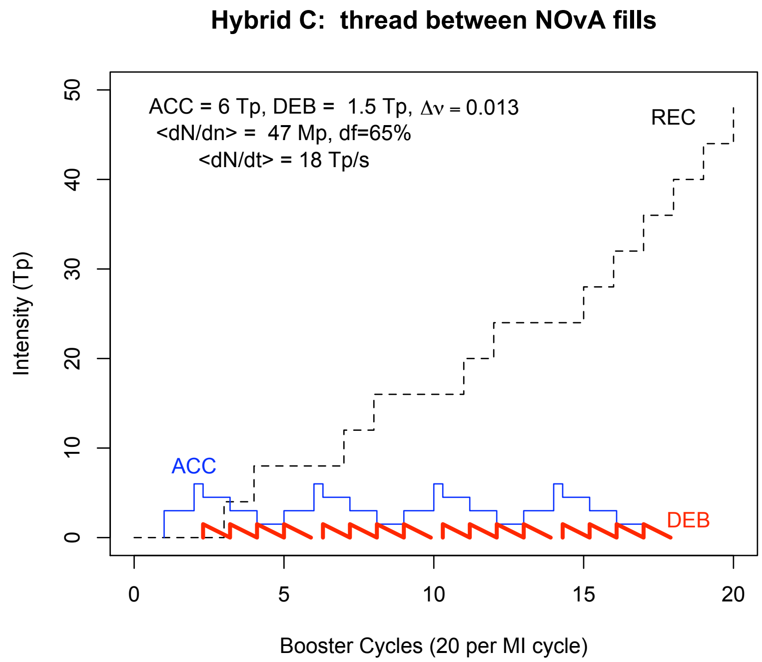

Figure 5: Another hybrid variant utilizing all 8 available Booster cycles, maintaining 18 Tp/s using lower intensities. A 20 ms bunch preparation time is assumed, with a 90% duty factor per spill.

The technique can be used to further reduce intensities by using all 8 available Booster pulses during the MI cycle, though a faster bunch formation would be desired to take full advantage. Suppose that momentum stacking and 2.5 MHz bunches could be formed all within 20 ms; then a scenario as shown in Figure 5 could be contemplated. In this figure the average rate of 18 Tp/s is maintained by scaling back the intensity of the Booster to 3 Tp and again forming 4 bunches to be directed into the Debuncher in four separate spills. However, once the spill time is less than a Booster cycle, the process becomes more inefficient, as transfers to the Accumulator obviously cannot be made until it is empty. The duty factor to the experiment would be less, accordingly – about 65% in this example. (For this discussion, the four Debuncher spills are kept at equal lengths of time.) However, the ring intensities are dropped by factors of 2 and 8 in the Accumulator and Debuncher, respectively.

The point to be made here is that the hybrid scheme allows for various optimizations of intensities, spill lengths, duty factors, *etc.*, as run conditions change, experience is gained, and overall HEP program plans evolve – all-the-while using the same basic kicker and RF system configurations. Additionally, the lower duty factor scenarios just described can be readily extended to 90^{+}% duty factor running in the absence of NOνA (such as during down time for repairs, *etc.*).

Note that for all of the duty factors quoted above, assumptions have been made regarding the bunch preparation times and the spill times in order to compare scenarios. Details of the final configuration of hardware will dictate the final duty factor available to the experiment; the numbers used here are probably a little bit conservative.

4 Comparison Tables

Tables 1-4 compare various aspects of the schemes described above. By selecting a hybrid approach, the space charge issues can be scaled down considerably, while maintaining reasonable duty factor for the experiment. In addition, the use of an operating scenario which is flexible in its relation to the NOνA cycle would provide a much more robust route for the Mu2e program.

While Hybrid Schemes A and B are similar in terms of duty factor and instantaneous rate to the experiment, they will differ in kicker repetition rate requirements and RF voltages. (The higher intensity of A will require , while B will require higher kicker rates.) A preferred solution might be to design toward the higher intensity of A (higher voltage RF systems, as in the Baseline) along with higher kicker rates for B. This enables both solutions, while C could be enabled later with an upgrade of the rep rate of the final kicker systems. Note that the $h = 1$ RF systems of the Baseline (for the Accumulator and the Debuncher) are no longer required.

In Hybrid Scheme A, the space charge (Debuncher intensity) is reduced by a factor of 4 while the Baseline instantaneous rate is maintained, and the Recycler kicker requirements are consistent with kicker development required for NOνA. If difficulties dealing with this level of intensity in either the Accumulator or Debuncher are encountered, Scheme B could be readily implemented, where the space charge is down a factor of 6 from the Baseline, the instantaneous rate to the experiment is increased by only 10%, and the overall duty factor to the experiment is over 80% (and could be at its baseline figure of 90% if the entire timeline were available to Mu2e). With NOνA off, the experiment has the capability of receiving protons at the same instantaneous rate but at a 20% higher average rate.

If troubles with high current occur even with solution B, then intensities could be backed off toward a solution along the lines of C with a kicker upgrade. In all cases, spill times are on the scale of 50-150 ms which is thought to be long enough for slow extraction to be developed and spilled within tolerable rates. Schemes A and B use only 6 of the available 8 Booster cycles, allowing for other programs to use the remaining pulses, or providing contingency within the Mu2e scheme.

A next step will be to properly evaluate the requirements of the RF systems to be used in the hybrid scheme, and the space requirements and allocations in the Recycler tunnel and service buildings necessary for the RF and kicker systems.

Table 1: Comparison Table I — Duty Factors

	Expt Cycle (BOO)	Cycle Time (ms)	Spills per Cycle	Cycles per MI	bunch form time (ms)	spill time (ms)	max df	NOνA Off max df
BASELINE	10	666.7	1	2	133.3	600	90%	90%
Full Rate (g-2) A	1	66.7	4	6	(REC)	15	27%	90%
Full Rate (g-2) B	1	66.7	4	8	(REC)	15	36%	90%
Hybrid A	10	666.7	4	2	33.3	150	90%	90%
Hybrid B	6	400.0	4	3	33.3	90	81%	90%
Hybrid C	4	266.7	4	4	20.0	54	65%	81%

Table 2: Comparison Table II — Intensities

Scenario	Expt cycle (BOO)	BOO pulses per cycle	BOO Int. (Tp)	DEB int. (Tp)	inst. $\langle dp/dn \rangle$ (Mp)	ave. $\langle dp/dt \rangle$ (Tp/s)	$\langle dp/dt \rangle$ NOvA off (Tp/s)	DEB Sp. Chg. $\delta\nu$
BASELINE	10	3	4	12	34	18	18	0.1
Full Rate (g-2) A	1	1	4	1	113	18	60	0.008
Full Rate (g-2) B	1	1	3	0.75	85	18	45	0.006
Hybrid A	10	3	4	3	34	18	18	0.025
Hybrid B	6	2	4	2	38	18	20	0.017
Hybrid C	4	2	3	1.5	47	18	22.5	0.013

Table 3: Comparison Table III – RF Systems

Scenario	Expt cycle (BOO)	REC rf	ACC rf	DEB rf	ACC stacking
BASELINE	10	n/a	h=84,4,1	h=4,1	YES, 3
Full Rate (g-2) A	1	h=588,56,28	h=4	h=4	NO
Full Rate (g-2) B	1	h=588,56,28	h=4	h=4	NO
Hybrid A	10	n/a	h=84,4	h=4	YES, 3
Hybrid B	6	n/a	h=84,4	h=4	YES, 2
Hybrid C	4	n/a	h=84,4	h=4	YES, 2

Table 4: Comparison Table IV – Kicker Systems

	Cycle (BOO)	REC out	ACC in	ACC out	DEB in
max rate (Hz)					
BASELINE	10	dipole	15	pulsed	pulsed
Full Rate (g-2) A	1	15	15	60	60
Full Rate (g-2) B	1	15	15	60	60
Hybrid A	10	15	15	6	6
Hybrid B	6	15	15	10	10
Hybrid C	4	15	15	16	16
ave rate (Hz)					
BASELINE	10	n/a	4.5	1.5	1.5
Full Rate (g-2) A	1	4.5	4.5	18	18
Full Rate (g-2) B	1	6	6	24	24
Hybrid A	10	4.5	4.5	6	6
Hybrid B	6	4.5	4.5	9	9
Hybrid C	4	6	6	12	12
ave rate (Hz), NOνA Off					
BASELINE	10	n/a	4.5	1.5	1.5
Full Rate (g-2) A	1	15	15	60	60
Full Rate (g-2) B	1	15	15	60	60
Hybrid A	10	4.5	4.5	6	6
Hybrid B	6	5	5	10	10
Hybrid C	4	7.5	7.5	15	15